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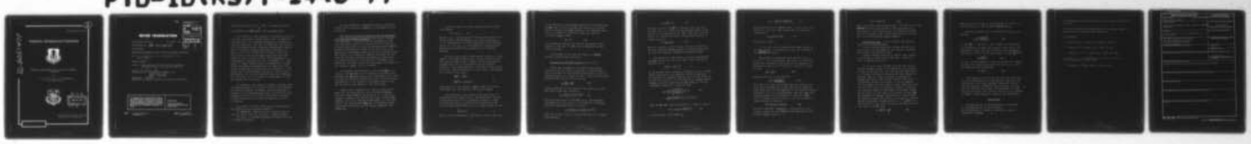

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by

A. A. Vorob'yev, O. B. Yevdokimov,
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FOREIGN TECHNOLOGY DIVISION

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Charging dielectrics with a beam of charged particles

by

A.A. Vorobyev, O.B. Evdokimov, and V.N. Gusel'nikov

The interest in the charging of macroscopic particles of matter has grown in recent years. This is connected with the desire to accelerate macroscopic particles to high velocities with the goal of modelling the behavior of micrometeorites, and initiating thermonuclear fusion [1]. In addition, charged macroscopic particles are used as "fuel" in reactive electrostatic motors. The means usually used in sharging macroscopic particles inpart to them a surface sharge. The development of acceleration technology has made it possible, in recent years, to give a volume charge to dielectrics, through irradiation [2] by fast electrons or gamma rays. This method allows one to charge the entire volume of a dielectric with cross-sectional area up to several square centimeters. The charge deposited within the dielectric by this method can be so large that discharge, or even spallation, sets in rapidly.

The deposition of charge in volumes of matter opens new possibilities in the investigation of the processes of electron trapping, breakdown, electron mobility in dielectrics and semiconductors. Also the effect of self-charging in a series of highly radioactive substances on their catalytic and absorptive properties can be determined.

The problem of charge deposition in dielectrics by fast electrons has two basic aspects:

(1) transport, moderation, and thermalization of fast electrons, with the creation of volume charge;

(2) drift, capture by trapping, and neutralization of thermal electrons.

In this article we investigate certain theoretical spects of the build-up of charge in dielectrics by fast electrons.

The Theory of Charge Build-up in the Approximation of Effectively Mobile Electrons. The motion of electrons arrested in the dielectric is considered in [3], from the point of view of an investigation of the concentration and depth at which the electrons are trapped. In the accumulation of charge in the dielectric it is important to distinguish deep and surface trapping sites. The latter, to a significant degree, determine the mobility of carriers, and hence determine the limitations of charge build-up in the dielectric. The deep sites determine, all other conditions being equal, the value of the residual charge, and its duration.

The maximal stored charge in the dielectric, naturally, is determined by the current of the beam of electrons, and the properties of the dielectric, among which are specific electric conductivity, the type of carrier, the mobility of the carriers, and their concentration, and the density and depthes of the trap sites.

These latter properties, in turn, to some extent depend on the beam current, and the absorbed dosage. necessary conditions for the build-up of a significant amount of charge in the dielectric, under lectron bombardment, are: small specific conductivity for the dielectric, and low electron mobility. For example, photoconductors can not be used for charge deposition via radiation.

Analysis shows that large charge build-up is most likely when:

$$e\mu n \gg e_+ \mu_+ n_{+0} \; ; \qquad n > n_0 , \tag{1}$$

where n is the concentration of the electrons which have accumulated in the dielectric, $\mu$ is their mobility, $n_0$ is the concentration of "free" electrons at equilibrium, and $e_+$, $\mu_+$, and $n_{+0}$ are the respective concentration, mobility, and equilibrium concentration of positive charges.

We will examine the accumulation of charge in a dielectric fulfilling condition /1/, assuming that the concentration of deep sites is small, and the influence of surface sites can be accounted for by the effective mobility $\mu$. The concentration of electrons n(x,t), accumulated in a plate dielectric, in this case, is determined by a system of equations:

$$\frac{\partial E(x,t)}{\partial x} = -\frac{en(x,t)}{\varepsilon} ; \tag{2}$$

$$\frac{\partial n(x,t)}{\partial t} = g(x,t) + \frac{\partial}{\partial x}(\mu n E), \tag{3}$$

where g(x,t) is the density, per unit time, of arrested electrons, i.e. the source of the volume charge.

The magnitude of the charge in the plate will be determined by the properties of the dielectric, and not by the properties of the surrounding medium. In order to determine boundary conditions we suppose that the plate is short-circuited, that is, at any instant of time

$$\int_0^l E(x,t)\,dx = 0, \tag{4}$$

where $l$ is the thickness of the plate. (We note that the

above condition on the ineffectiveness of the surrounding medium holds for the case when the plate is in contact with a conductive medium). Condition (4) indicates that, in fact, inside the dielectric there is a point of zero field $x=x_0$ at which

$$E(x_0,t)=0. \qquad /5/$$

In the general case the location of the point of zero field is a function of time, and is determined by the form of $g(x,t)$.

In practice we meet with two types of electron sources: steady-state and pulsed.

Steady-state Electron Sources, $g(x,t)=g_0(x)$

Within the framework of the model under examination the limiting values $n(x,t\to\infty)$ and $E(x,t\to\infty)$ can be obtained from the random distribution of arrested electrons $g_0(x)$. In as much as when $t\to\infty$ we have $\partial n/\partial t\Rightarrow 0$ then from /2/ and /3/ it follows that

$$\frac{d}{dx}\left(\frac{dE_\infty^2}{dx}\right)=\frac{2eg_0}{\mu\varepsilon}. \qquad /6/$$

Taking condition /5/ into account, we obtain, as $t\to\infty$ the field inside the dielectric

$$E_\infty=\pm\sqrt{2e/\mu\varepsilon}\,\left(\int_{x_0}^{x}dx'\int_{x_0}^{x'}g_0(x'')\,dx''\right)^{1/2}, \qquad /7/$$

where the plus sign is used when $x<x_0$, and the minus sign when $x>x_0$. The limiting distribution of electron density is obtained from /7/ and /2/:

$$n_\infty=\sqrt{\varepsilon/2\mu e}\int_{x_0}^{x}g_0(x')\,dx'\left(\int_{x_0}^{x}dx'\int_{x_0}^{x'}g_0(x'')\,dx''\right)^{-1/2}. \qquad /8/$$

Then tha absolute value of the maximum charge in a plate with density S

$$Q_\infty = eS\int_0^l n_\infty(x)\,dx. \qquad /9/$$

The point of zero field $x_0$ is determined from /4/. From equation /9/ it is clear that the maximum charge in the dielectric is proportional to $\sqrt{\varepsilon/\mu}$. From this, in particular, it follows that with a uniform distribution of sources $g_0(x)=g_0$

$$Q_\infty = (e\varepsilon g_0/\mu)^{1/2} l S, \qquad /10/$$

where we have put $x_0=l/2$. We now turn our attention to the fact that the maximum charge is proportional to $\sqrt{g_0}$, as with self-charging radioactive preparations [4].

The dynamics of the charge in time are determined by equations /2/ and /3/. From these there follows an equation for E

$$\frac{\partial}{\partial x}\left(\frac{\partial E}{\partial t} - \mu E\,\frac{\partial E}{\partial x}\right) = -\frac{eg}{\varepsilon}. \qquad /11/$$

In the general case obtaining a solution to /11/ in elementary functions is not possible. Finite formulas can be obtained, for example, when $g(x)=g_0$. In this case, as may be seen from /8/, the distribution of charge remains uniform as $t \longrightarrow \infty$, hence $E(x,t)=(l/2-x)E_0(t)$, and the solution of equation /11/ has the form

$$E(x,t) = \left(\frac{eg_0}{\varepsilon\mu}\right)^{1/2} \frac{\exp\left[2\left(\frac{e\mu g_0}{\varepsilon}\right)^{1/2} t\right]-1}{\exp\left[2\left(\frac{e\mu g_0}{\varepsilon}\right)^{1/2} t\right]+1}\left(\frac{l}{2}-x\right) = \qquad /12/$$

$$= \left(\frac{eg_0}{\varepsilon\mu}\right)^{1/2} th\left[\left(\frac{e\mu g_0}{\varepsilon}\right)^{1/2} t\right]\cdot\left(\frac{l}{2}-x\right) = E_0(t)\cdot\left(\frac{l}{2}-x\right).$$

where th $\equiv$ tanh. The distribution of charge in time is

$$n(x,t) = (e\varepsilon g_0/\mu)^{1/2}\, th\left[\left(\frac{e\mu g_0}{\varepsilon}\right)^{1/2} t\right] \qquad /13/$$

and the charge of the plate is

$$Q(x,t) = -\left(\frac{e\varepsilon g_0}{\mu}\right)^{1/2} lS\, th\left[\left(\frac{e\mu g_0}{\varepsilon}\right)^{1/2} t\right]. \qquad /14/$$

From equation /14/ it follows, that if $t \to \infty$ then /14/ reduces to /10/. The time required for the charge to accumulate is

$$t_K = (\varepsilon / e\mu g_0)^{1/2} \mathrm{Arth}\,(K/100). \qquad /15/$$

where Arth $\equiv \tanh^{-1}$.

It is clear that the accumulation time lessens as the beam current is increased, or with the increase of the ~~leeetron~~ electron mobility.

The process of discharge after the radiation is shut off is also interesting. The process of discharge, within the framework of the model we are assuming, is described by equation /11/ with $g=0$ ; from this there follows

$$\frac{\partial E}{\partial t} - \mu E \frac{\partial E}{\partial x} = 0. \qquad /16/$$

Equation /16/ has as its solution

$$E(x,t) = \frac{E_0(t_0)\left(\frac{l}{2} - x\right)}{1 + \mu_0 E_0(t_0)(t - t_0)}, \qquad /17/$$

where we have taken into account the fact that at time $t = t_0$, when the radiation is shut off $E(x,t)$ takes its value from /12/, and the mobility of the electrons without radiation $\mu_0$ is to be distinguished from the value this quantity assumes in the presence of radiation. From /17/ it follows that the charge of the plate changes in time according to the law:

$$Q(t) = -\varepsilon l S E_0(t_0)/1 + \mu_0 E_0(t_0)(t - t_0). \qquad /18/$$

With the condition $1 \ll \mu_0 E_0(t_0)(t - t_0)$ the behavior of the charge in time does not depend on the magnitude of the initial charge, that is:

$$Q(t) = -\varepsilon l S/\mu_0(t-t_0), \qquad /19/$$

and is determined exclusively by $\varepsilon/\mu_0$. However, it must be noticed that for large values of the quantities $t, t_0$ the charge of the dielectric will be determined by the depth of the sites, and in this case formula /19/ does not give a sufficiently precise answer.

Pulsed Radiation. In this instance two limiting cases must be distinguished:

First: Electron mobility is large, and the residual charge, at the moment of the arrival of subsequent pulses is practically zero;

Second: Electron mobility is small, and a significant number of pulses must arrive for a condition close to saturation occurs.

In the first case formulas /14/ and /18. can be adopted without change. In the second it is necessary to take into account the fact that in the sample there is a charge, the value of which grows from impulse to impulse. When the number of pulses, necessary for charge saturation, have arrived several times over, it is possible, without difficulty, to obtain formulas for the dynamics of the charge in time, using equations /11/ and /16/. With still greater numbers of impulses the formulas become to cumbersome. The maximum charge can be obtain, if one takes into account the fact that the condition of dynamic equilibrium is characterized by equality between the charge in the pulse $q_u$, and the charge neutralized between pulses.(It is assumed that the loss during the pulse arrival may be ignored). Then from /18/ it follows that

$$q_u = \frac{\mu_0 Q_0^2 T}{\varepsilon l S} \Big/ 1 + \frac{\mu_0 Q_0 T}{\varepsilon l S}, \qquad /20/$$

where $Q_o$ is the charge of the dielectric at the end of the pulse, and T is the interval between pulses.

Solving equation /20/ for "maximum" charge $Q_o$, we obtain:

$$Q_o = \frac{q_u}{2} + \sqrt{\left(\frac{q_u}{2}\right)^2 + \frac{\varepsilon l S}{\mu_o T} q_u}\ ; \qquad /21/$$

If $\frac{q_u}{4} \gg \frac{\varepsilon l S}{\mu T}$, then $Q_o \approx q_u$. This happens in cases where it is possible to ignore the length of the pulses, the mobility is large, and the dielectric has discharged at the time of arrival of the next pulse. With $\frac{q_u}{4} \ll \frac{\varepsilon l S}{\mu T}$ then

$$Q_o \approx \sqrt{\frac{\varepsilon l S}{\mu_o T} q_u}\ . \qquad /22/$$

This is the more realistic case. The result /22/ reduces to /10/ if we take into account the fact that $g_o$ and $q_u$ are connected by the relation

$$q_u = e g_o l S T, \qquad /23/$$

The identity of relations /10/ and /22/ indicates, that with either pulsed or steady-state radiation, for a dielectric with large internal conductance and low electron mobility, maximum charge is stored. However, one must remember that $\mu > \mu_o$, and therefore, all other things being equal, with pulsed radiation it is possible to store a larger amount of charge in the dielectric.

## Conclusions

Maximum charge in the dielectric is determined by the magnitude of the beam current.
The accumulation of charge in time obeys a law of hyperbolic tangents

The discharge of the dielectric follows in inverse proportion to the time.

With pulsed radiation the magnitude of the maximum charge is greater than with steady-state radiation.

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